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Sense of moving

Moving closer to the movement

Mark Schram Christensen and Thor Grünbaum

Introduction

This chapter is about the relationship between active movement and the sense of agency (SoA). We present two ideas. The first idea concerns the sense of active movement. Without much argument, we will assume that there exists a sense of “movement activity” that arises, for instance, when I actively lift my index finger from the table: A minimal feeling of physical activity, in this case, a feeling of bodily activity involved in lifting the index finger. This sense is usually supposed to be part of SoA. The second idea is about the standard experimental paradigms used to study SoA. The purpose of the chapter is to determine whether the already existing paradigms can be used to study the sense of movement activity, i.e. the part of SoA related to actual movement. The bulk of the chapter is an argument to the effect that standard paradigms are ill equipped to study the sense of movement activity. Standard paradigms target the attribution of agency for the *consequences* of active movement rather than the sense of movement itself. These paradigms nearly always confound the sense of movement activity and the active prediction of the consequences of the movement.

In this chapter, we proceed as follows. We start by motivating the assumption of a sense of movement activity. We proceed to discuss ways in which this sense of movement is related to SoA and present an overview of dominant theories of SoA in contemporary cognitive neuroscience. This will not be an exhaustive systematic review of available theories and definitions of SoA; rather, we aim to describe the theories of SoA in the context of our overall question: What aspects of the action are studied in studies of SoA? The subsequent section describes the types of experimental paradigms that have been used in the study of SoA. In particular, we aim to understand what part of the movement, from preparation to delayed action effects, has been studied using these typical paradigms. We end the chapter with a brief evaluation of whether all relevant aspects of the movements are included in the studies of SoA, or whether further or different kinds of studies are needed in order to directly address the sense of movement activity.

A sense of movement activity

According to prevailing cognitive theories of movement control, one essential aspect of movements is SoA – that is, the sense of being in control of one’s own movements, i.e. being the agent of one’s movements. We are supposed to have this SoA most of the time (Haggard & Chambon, 2012), and it provides us with an ability to distinguish our own movements from other’s movements (see e.g. David, 2012; Georgieff & Jeannerod, 1998).

Based on this idea of SoA, a number of interesting proposals can be made in terms of the types of behaviours and experiences participants would display in various experimental studies, for instance, illusory sensations of having made a voluntary movement. We will present some of the ideas concerning SoA and assess the extent to which current experimental approaches are able to address the types of behaviour and experiences in question. In particular, we will address one particular aspect of SoA studies, namely, the relation between SoA and real movements, on one hand, and SoA and transformed consequences of movements, such as visual representations of a movement as a dot on a computer screen, on the other hand. Based on these considerations, we hope to demonstrate that most studies of SoA are actually not studying sense of control of *movements*, but rather sense of control of transformed *consequences* of movements. This suggests that further studies are needed to address the sense of control of real movements, and that these studies may in fact lead to a revision of the current theories of SoA.

In this chapter, we assume that there is a special sense of activity associated with the performance of particular movements (rather than distal consequences of movements). When I place my hand on the table in front of me and lift my index finger, I have a clear experience of moving my finger upwards. From the use of such simple thought-examples, it seems intuitively appealing that there is a sense of activity directly related

to one's bodily movement. The extent to which this experience is clear or not may depend on the amount of attention paid to the movements, however, we will assume such an experience of moving exists and that it is tightly coupled to the SoA.

Furthermore, a body of experimental literature suggests that there is a distinct type of experience related to the movement. These studies have either used direct electrical cortical stimulation during surgery (Desmurget et al., 2009; Fried et al., 1991) or indirect cortical stimulation (Amassian, Cracco, & Maccabee, 1989; Christensen et al., 2010) using transcranial magnetic stimulations (TMS). These experiments indicate that participants experience a sensation of movement or urge to move directly related to the movement rather than a delayed or transformed sensory representation of the movement.

Based on these considerations, we aim to explore studies that are related to the SoA of movements and determine the extent to which contemporary experimental studies enable us to understand the relationship between SoA (more broadly conceived) and sense of movement activity.

Definitions and models of SoA

Assuming that there is such a thing as a sense of movement activity, the next question becomes how do various frameworks conceive of and explain this phenomenon? Thus, before moving on to our central problem of experimental paradigms, we want to take a closer look at how the phenomenon is conceptualized and explained by prevailing definitions and models of SoA.

Definitions of SoA

SoA can be defined along various dimensions. Here we focus on two. The first dimension concerns the extent to which action consequences are included in the definition of SoA, whereas the second is a functional dimension concerning the degree to which SoA is conceived of as a particular cognitive ability. In Figure 4.1, we have sketched these two dimensions along perpendicular axes.

The first dimension of variation important for definitions of SoA in the present context concerns the scope of action and SoA. SoA can be given either a narrow definition, focusing exclusively on the movements, or a broad definition, including also the consequences of one's movement. The narrowness or broadness of the definition seems to depend on how one would single out an action. According to the narrow approach, the action is more or less the agent's voluntary movement, whereas according to the broad approach, the agent's action is often thought to include the foreseen effects of the movement in the environment. On the narrow definition of action, SoA could be conceived of in terms of Libet-like urges to move and kinaesthetic sensations of movement (Libet, Gleason, Wright, & Pearl, 1983; see also Farrer, Franck, Georgieff et al., 2003, p. 324, "When we act, we normally feel ourselves causing and controlling our own action", and De Vignemont & Fournier, 2004). On the broader definition of SoA, the SoA is not related only to the movement but equally to the planned consequences of the movement. Proponents of this broader definition would conceive of SoA not only in terms of intentions or urges to move but equally in terms of predicted or planned consequences, that is, prediction of sensory events such as switching on the light or causing a sound when hitting a drum.

The broad conception of SoA is probably dominant in contemporary cognitive neuroscience. To give the reader a flavour of the many different and sometimes inconsistent broad descriptions of SoA, consider the following quotes. Tsakiris, Prabhu, and Haggard defined SoA as: "Agency is the sense of intending and executing actions, including the feeling of controlling one's own body movements, and, through them, events in the external environment" (Tsakiris, Prabhu, & Haggard, 2006, p. 424). This definition is not only about experiencing oneself as the agent of the action but rather about the experience of (1) intending an action, (2) executing an action, (3) controlling one's body, and the experience that (4) the body produces events in the environment. According to Tsakiris' definition, it is, however, not entirely clear whether all four aspects of a movement need to be present in order to experience SoA. Nevertheless, it might provide us with a good description of the various aspects of an action, which may give rise to a SoA. A similar inclusion of action consequences is also present in a definition offered by Balconi and Crivelli. According to them, SoA is the sense that "I am the one who is causing or generating an action or thought and all related effects, differently to the sense that I am the one undergoing an experience, defined as sense of ownership" (Balconi & Crivelli, 2009, p. 182).

Taking a more analytic line, Pacherie argues: "The sense of agency for a given action; i.e. the sense the agent has that he or she is the author of that action, can, I shall argue, be analyzed as a compound of more basic

experiences. Most prominent among these component experiences are the experience of intentional causation, the sense of initiation and the sense of control" (Pacherie, 2007, p. 2). Thereby, Pacherie suggests that SoA is a complex experiential whole with more primitive experiences as parts.

In contrast to Pacherie's more direct focus on the phenomenology, a more mechanistic definition of SoA is due to Patrick Haggard (2005). According to Haggard, SoA arises in the integration of efference copy signals (von Holst & Mittelstaedt, 1950) (copies of motor command signals, see also subsection *Comparator model*) with predicted feedback and sensory information. This definition is based on the proposals by Frith, Blakemore, and Wolpert (2000). When there is no discrepancy between the two, SoA arises. In a 2008 review, Patrick Haggard (2008) extends the notion of SoA into various levels of representation: On top, there is a self-representation level, which gives rise to an experience of Self as Agent; this level rests upon an action-representation level, where the experience is a "*Sense of voluntary control: 'I did that'*". This level again rests upon so-called binding processes, including prediction and reconstructive inference, which then again rests upon a level of conscious experiences of intention, action, and outcome, where each of these is governed by neural events of motor preparation, movement, and sensory effects, respectively.

The second dimension of variation important for definitions of SoA in the present context concerns conception of SoA as a particular cognitive function or ability. On the one hand, we have researchers who conceive of SoA as a primitive ability for self-other discrimination, and, on the other hand, we have researchers who think of SoA as simply a primitive phenomenal feeling ("*we have a definite background feeling or buzz of being in control*", Kühn, Brass, & Haggard, 2013, p. 1936). Focusing on the first side, one important motivation for studying SoA has been the proposed relation between SoA and the agent's ability to make self-identification judgements. One important hypothesis has been the idea that this ability to identify oneself rests upon the ability to assign the correct agent to an action (Georgieff & Jeannerod, 1998; Jeannerod, 2006). The idea here is that an agent's ability to identify her own body should be understood in terms of an ability to distinguish between one's own body and the body of some other person. Consequently, a large field of research has evolved that deals with the distinction between self and other in correctly ascribing agents to actions.

This second dimension differs in many ways from the first. For one thing, the two extremes (specific ability vs. phenomenal feel) are not two opposite end points of a common continuum. It is perhaps better to describe them as the two sides of a fundamental metaphysical and methodological choice. Either we conceive consciousness in functional terms as something that enables a cognitive ability or we conceive of consciousness as a primitive phenomenal state. That theories of consciousness are in fact confronted with this fundamental choice is apparent from recent debates about visual consciousness (Block, 2011; Cohen & Dennett, 2011; Cohen, Dennett, & Kanwisher, 2016; Kouider, De Gardelle, Sackur, & Dupoux, 2010; Lamme, 2010) and the more general controversy between cognitive and non-cognitive theories of consciousness (Block, 1995; Dehaene, 2014). It is a version of this fundamental choice that also confronts researchers in the domain of motor control.

In the present context, the definition of SoA as an ability for self-other discrimination is not without problems. If the SoA is fundamentally a question of self-other discrimination, then, given that SoA is thought to be pervasive and the ability to distinguish between different agents thereby thought to be fundamentally related to control of movement, we should expect that this type of discrimination task makes sense to participants in a large variety of situations. This is by no means obvious. When I lift my index finger from the surface of the table without others being present, it is not obvious that I am performing a kind of self-other discrimination task. Despite the fact that issues concerning self-identification are an important factor motivating many studies of SoA, it is not obvious that it always (or even often) makes sense for the participants in the relevant types of agency experiments to engage in self-other discrimination tasks. In any case, in order to study SoA by studying the self-other distinction, one is faced with the requirement of presenting situations in which the self-other distinction becomes important for the participant; otherwise, the study of SoA becomes a study of an artificial construct that does not make sense to participants.

Therefore, one may ask whether the self-other distinction is an important and necessary distinction to make during all types of movement. The issue can be articulated in terms of two conflicting positions concerning the nature and role of SoA in control of movements. The first position characterises SoA in terms of self-identification and operationalises it in terms of the ability to discriminate between self and others. According to this position, experiments performed in the domain of SoA assume that self-other

discrimination tasks are a valid way to study voluntary movements and their associated agency experiences. The second position does not characterise SoA in terms of self-identification. Consequently, according to this position, typically, SoA should not be operationalised in terms of self-other discrimination tasks.

The two dimensions can combine. Both the ability conception and the simple phenomenal conception of SoA come in narrow and broad versions. For the remainder of this chapter, we will set aside the conception of SoA as the ability for self-other discrimination. The focus in this chapter is the sense of movement activity, and it seems unlikely that the majority of possible paradigms for investigating this sensation of movement would be paradigms where it makes sense for the participants to make self-other discriminations. In the next section, we will argue that prevailing explanatory models differ with respect to which notion (narrow or broad) SoA they employ. Finally, we will argue that current experimental paradigms are unable to study SoA in the narrow sense, for which reason these paradigms in many cases will be incapable of distinguishing between different models.

Models of SoA

In this section, we will briefly review some of the most influential theoretical considerations that have informed studies of agency the last 15–20 years. We will not make in-depth descriptions of the various studies supporting each of the different theoretical approaches to SoA but give a quick overview and point to some important differences and similarities (for a more detailed presentation, see the chapter by Jensen, Dong, Vinding, and Overgaard, Present volume).

A number of theoretical models have been proposed to explain SoA. One branch includes low-level basic sensorimotor models derived from the efference copy motor literature, which originally focused on the execution of movements, but in the context of SoA has been extended to include sensory consequences of movements outside the body. In other words, this type of model seems best suited to explain SoA in a narrow sense but has often been applied to SoA in the broad sense (see Figure 4.1 for an outline of the difference between SoA in a narrow and a broad sense). Another branch includes Daniel Wegner-style models, which deal with the sensory consequences of movement. Furthermore, hybrid models such as the cue integration model combines the two previous models, and finally, Bayesian integration models, which can be considered higher-order models, are trying to explain several different phenomena and different levels of description using one explanatory mechanism.

Comparator model

The probably most influential model of sense of agency has been the comparator model proposed among others by Frith et al. (2000). The idea with the comparator model is that any voluntary movement is produced by motor command signals and that these signals are accompanied by efference copy signals (Sperry, 1950; von Holst & Mittelstaedt, 1950), which are used to make a prediction of the sensory consequences of the movement, using a so-called forward model. The outcome of the forward model is the predicted sensory feedback caused by a given movement. The predicted sensory consequences are made available to a comparator module. This part of the mechanism carries out a comparison between the predicted and actual feedback caused by the actual movement. When the comparison reveals that the predicted sensory feedback matches the actual sensory feedback, sense of agency arises. When there is a discrepancy between the predicted and actual sensory feedback, one has a diminished or no sense of agency. The comparator model has also been denoted the central monitoring theory (see Jeannerod, 2006). As we will see in the next sections, although this model was originally tied to the motor system, it has been applied to the prediction of other kinds of sensory consequences as well.

Apparent mental causation

Another kind of comparison model is the “theory of apparent mental causation” proposed by Wegner (2002). According to Wegner’s theory, the experience of wilfully being able to control one’s actions is an illusion. The idea is that: “People experience conscious will when they interpret their own thought as the cause of their action” (Wegner, 2002, p. 64). The claim is that a nonconscious psychological event is the common cause of, on the one hand, an action and, on the other hand, a conscious representation. If the conscious representation occurs

prior to the action, the subject will experience it as the cause of the action. This model has been almost exclusively used to explain judgements of agency for distal effects of action. It was not intended as an explanation of the sense of movement activity or narrow SoA. We therefore leave this model aside.

Cue integration model

Another influential model that has been proposed to account not only for data in favour of the comparator model but equally Daniel Wegner's postdictive theory of apparent mental causation is the cue integration model (Synofzik & Vosgerau, 2012; Synofzik, Vosgerau, & Newen, 2008). According to this model, a cue integration mechanism is fed information from the sensorimotor system, background information about the environment, background beliefs, and sensory information. Although sometimes not explicitly acknowledged, the cue integration model borrows from Bayesian statistics by using priors in the formation of predictive mechanisms, which are part of the model. The integration of all of this information gives rise to a SoA in the broad sense. The narrow SoA related to the execution of movements is explained in terms of a comparator mechanism. Thus, with respect to a narrow SoA, there is no relevant difference between the comparator model and the cue integration model of SoA.

Active inference model

The final model we will describe is the active inference model of agency proposed by Karl Friston (see Friston, Samothrakis, & Montague, 2012; Friston et al., 2013), which is part of a general theory of free energy minimization as a principle for all brain processes (Friston, Kilner, & Harrison, 2006). In the active inference formulation of motor control, signals from the motor cortex to the spinal cord are considered as proprioceptive predictions rather than motor command signals (Adams, Shipp, & Friston, 2013). The active inference idea builds upon the predictive coding framework, in which perception is considered an active process that is based on an individual's predicted causes of the received sensory signals. These predictions rest upon prior knowledge mixed with the sensory signals in a Bayesian fashion in order to give rise to perception. Active inference is a natural consequence of this particular line of thinking, where perception can change either by changing one's prior belief or by sampling the environment differently through actions. According to the active inference definition of agency, SoA is a probabilistic representation of a state that represents the consequences of action. This may sound very much like the output from the forward model in the comparator model approach to SoA, but it precludes the comparator element between the predicted consequences of the movement and the actual movement. This also provides studies of agency with an interesting aspect, according to which an agent does not need to evaluate the actual sensory consequences of a movement in order to experience (a sense of) agency. This model seems equally suited to the explanation of SoA in a narrow and broad sense.

Discussion of models

The various definitions of SoA and theoretical models describing SoA reveal many important differences. First, it is evident that some researchers seem to think the distinction between self and other is the main function of a SoA, and this distinction is reflected in the theoretical approach to SoA. The comparator model is often proposed as a framework for the mechanism enabling self-other discrimination and SoA. The framework of the comparator model builds upon the motor control principles of efference copies (von Holst & Mittelstaedt, 1950). The idea of the concept of an efference copy has been experimentally confirmed in animals such as the electric fish (Bell, 1981) and crickets (Poulet & Hedwig, 2006). The hypothesis is that efference copies serve the purpose of cancelling out the sensory consequences of the organism's own movements. This central cancellation makes it possible for these animals to sense stimuli as coming from outside the organism. The mechanism has also been shown to exist in humans (see section on sensory attenuation).

For the overall purpose of this chapter, the comparator is very appealing because it deals with signals closely related to the actual movement. However, contemporary studies of SoA usually adopt a broad conception and go well beyond the movements in the application of the comparator model. The model is often extended to account also for external consequences of movements. An intriguing aspect of the comparator

model when looked upon from an experimental design point of view is the extent to which the findings can truly be related to a comparison between predicted and actual sensory feedback. Under many experimental settings where manipulations are made of external sensory consequences of a movement, it is often argued that, for instance, changes in brain activity are due to differences when predicted consequences are compared with the actual consequences. But given the experimental situations, one is left with a question of whether the comparison is really made between the predicted and actual sensory feedback or whether it is rather a comparison between sensory feedback from different sensory modalities that do not match each other, for instance, with respect to evaluation of a movement's end goal.

The broader definition of SoA as involving predictions of sensory consequences in the external environment requires knowledge of events outside the body and may or may not also require completely different underlying mechanisms. This is a challenge in particular if one adopts a strict definition of the forward model as using efference copies to generate a prediction of the sensory consequences of the movement. According to such a framework, the agent predicts sensory consequences of her movement on the basis of signals only from the efference copy (computed from the motor commands that, say, lift the arm). Using only the forward model, the agent should be able to determine whether a movement, let us say lifting an arm, will lead to an additional button press and a resulting auditory event. It is not difficult to imagine a situation where predictions generated only by this mechanism would be impossible or wildly unreliable, in particular where, for instance, electronic circuits introduce delays when turning on the lights after pressing a contact. Generally speaking, it is hard to believe that our motor system should be the primary source of our knowledge of statistical correlations or co-occurrences in the world. In order to produce precise and reliable predictions of the consequences of her actions, the agent would need to draw on more general background knowledge of the world.

This way of arguing suggests that the forward model requires additional information in order to compute the sensory consequences of the movement beyond the interoceptive feedback it may cause. These additional pieces of information require accurate knowledge of external factors contributing to the external consequences of the movement. When using the comparator model approach, one assumes that the formation of a forward model about external sensory events is constructed exactly as the forward model of the internal sensory events. Along the same line of argument, one must also assume that the comparison between predicted and sensory consequences must take place at each level of processing in order to construct the SoA (when there is no discrepancy between predicted and actual sensory consequences). This hierarchical forward model approach has to our knowledge not been studied experimentally in relation to SoA (but see [Pacherie, 2007](#)), but the underlying neuronal circuitry responsible for such a hierarchical approach to forward models has been proposed by [Ramnani \(2006\)](#) to exist in circuits connecting the cerebellum with different fronto-motor areas of the cerebral cortex.

Within the cue integration framework, the problem of determining different levels of hierarchically nested comparator mechanisms has more or less been eliminated by the construction of a model that tries to incorporate information from many different sensory modalities as well as from other sources of knowledge. The model does not explain SoA (in the broad sense) as the exclusive comparator interplay between predicted and actual feedback but conceives of the SoA as appearing from the integration between many types of information, sensory as well as contextual information and prior knowledge. The basic sensorimotor comparator has a distinct role in producing a low-level feeling of agency (that is, SoA in a narrow sense), which serves as input to a more general model producing the agent's judgement of agency (that is, SoA in a broad sense). One way to interpret this cue integration framework would then be that the forward model and comparator module produces a low-level feeling of agency for the movement, whereas the more general model integrating background knowledge produces judgements of agency for external events. The cue integration model thus avoids the problems that beset the comparator model in explaining the comparator processes involved in the evaluation of external consequences of movements. However, as already indicated, with respect to a narrow notion of SoA, the two models are identical and thus make identical experimental predictions.

According to the active inference model, a common mechanism accounts for both sensation and movement. The model works on the principle of one mechanism that accounts for all aspects of the movement and the sensations. The parsimony of the approach makes it appealing to use as an explanation of underlying mechanisms of SoA. However, this sweeping generality is also a cause for concern. When one mechanism

explains all these phenomena, one might worry that the model provides little insight into the important particulars. If we were looking for neural correlates of SoA of this general mechanism, it would be difficult to avoid the conclusion that all structures and interactions behaving according to an active inference mechanism were related to SoA.

Summing up, in terms of mechanisms that may give rise to a SoA, there are proposals, as described previously, suggesting that comparator mechanisms may give rise to SoA (in narrow and broad senses). According to the cue integration model, motor commands, predictions, and sensory signals are combined with contextual information and all of it contributes to the SoA (broad sense). Finally, we also have the active inference model with its caveats described in the previous section, which does not leave any part of the brain untouched in relation to being part of a mechanism that could produce SoA (narrow and broad sense). One common property of all these models with respect to narrow SoA is that they explain the sense of activity narrowly related to movement in terms of interplay between predicted and actual proprioceptive feedback. This commonality makes it clear that we can imagine an alternative explanation.

One possible alternative explanation for SoA in the narrow sense, absent from the existing literature, is the notion that the sense of activity associated with active movement could be directly produced by motor signals. In other words, an alternative explanation of the sense of movement activity might be that the experience is directly related to motor commands. The information carried by motor signals might somehow be accessible to the agent and drive the agent's judgements about her motor activity (in the absence of other kinds of information). This alternative explanation can thus be contrasted with the various models discussed in this section according to which the narrow SoA should be explained in terms of the interplay between predicted and actual sensory feedback. As the next section will show, existing experimental approaches to the study of SoA tell us very little about the sense of movement activity and cannot be used to distinguish between the two types of explanatory models (narrow SoA as the outcome of motor commands vs. the outcome of the comparison between predicted and actual sensory feedback).

[Insert Figure 4.1 Here]

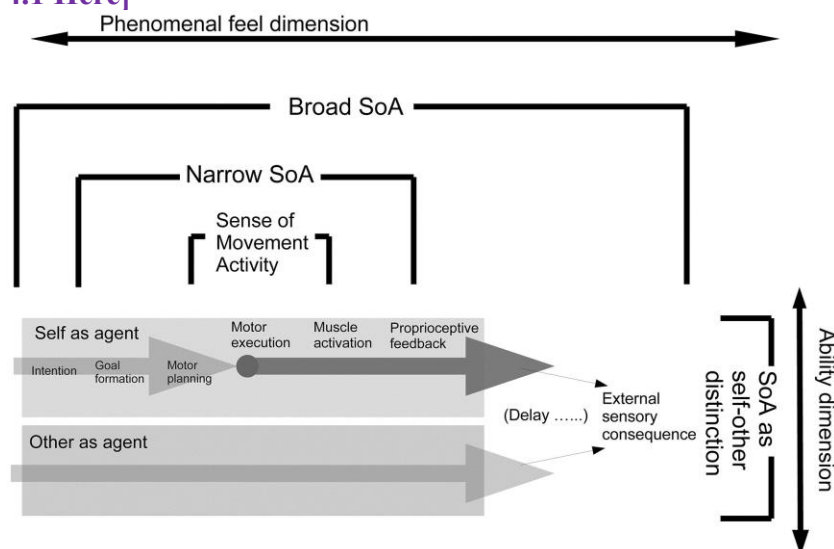


Figure 4.1 Sense of movement activity placed in context of narrow and broad SoA. The dot indicates the time of movement onset. We assume that there exists some kind of sense of movement activity temporally located around the time of the execution of the movement. According to a narrow view of SoA, SoA deals with processes internal to the agent, whereas the broad SoA also incorporates external sensory consequences of the movement. The narrow and broad SoA can be considered as different foci within an overall phenomenal feel dimension. On the other hand, SoA has been considered a question of making self-other distinction, which can be considered a judgement made along an ability dimension.

Experimental approaches to the study of SoA

In this section, we will give a rough overview of the experimental approaches that have been employed in the studies of agency carried out over the last 50–60 years. The purpose of the section is to determine whether the already existing paradigms can accommodate a narrow perspective on SoA, according to which a sense of movement activity is directly related to the actual movement.

In terms of experimental paradigms, there are broadly speaking three types of experiments. First, manipulations of the ongoing sensory feedback signal (typically visual), which are by far the most popular method to manipulate SoA. Second, studies of action-effect associations, in which the SoA is evaluated according to whether the participants feel that they produced some sensory consequence. Third, sensory attenuation experiments, where the sensory consequences of a movement are diminished when the movement is voluntarily performed.

Manipulation of feedback

Visual distortions

By far, the most important branch of SoA studies has been experiments in which the feedback generated by an action is manipulated in some way. Probably the most famous example of this is the alien hand experiment, designed by [Nielsen \(1963\)](#). Participants placed their hand inside a box and could view their hand through a slit. The participants were asked to draw straight lines on a piece of paper placed inside the box. Unbeknownst to the participants, the view of their hand was sometimes replaced by a mirror view of the experimenter's hand. In the situations where the experimenter starts to make line drawings that deviate from the drawings made by the participant, the participants apparently no longer experience that they made movements voluntarily. In post-experimental interviews inquiring into participants' experiences of SoA (or some similar construct), participants were asked to give a description of their experience.

These experiments have been replicated in numerous other studies using modern computer technology. [Fournier and Jeannerod \(1998\)](#) performed an experiment in which participants drew lines on a digitizing tablet with angular distortions of varying degrees up to 10° introduced by a computer algorithm. In one set of experiments, participants were asked to make a similarity judgement between their own motor performance and predefined lines. [Ritterband-Rosenbaum et al. \(2011\)](#); [Ritterband-Rosenbaum, Christensen, & Nielsen, 2012](#); [Ritterband-Rosenbaum, Karabanov, Christensen, & Nielsen, 2014](#); [Ritterband-Rosenbaum, Nielsen, & Christensen, 2014](#)) used a similar design where participants moved a cursor using a tablet from a starting point to different target positions with visual deviations. Participants were asked to indicate whether the movement they saw on the screen was made by themselves or the computer.

Other types of distortions have also been employed, such as the bimanual in-phase anti-phase hand opening and closing used by [Fink et al. \(1999\)](#), where the visual feedback sometimes was distorted using a mirror, so participants sometimes performed anti-phase left and right hand opening and closing but viewed in-phase left and right hand opening and closing due to the presence of the mirror. [Farrer, Franck, Georgieff et al. \(2003\)](#) performed an experiment in which participants controlled a virtual hand that was either in accordance with their own movement, rotated 25° or 50°, or controlled by an experimenter. [Balslev, Nielsen, Paulson, and Law \(2005\)](#); [Balslev, Nielsen, Lund, Law, & Paulson, 2006](#)) performed visuo-proprioceptive conflicts while participants performed mouse movements on a screen. The viewed movement of the cursor was either in accordance with their actual movement or a recording of a previous movement they had performed themselves. Others have used more advanced methods such as virtual gloves to turn real movements into computer representations ([Nahab et al., 2011](#)). In these experiments, anything from evaluating the strangeness of movement ([Fink et al., 1999](#)), reporting whether the displayed movement is their own, a distorted version of their own movement, or someone else's movement ([Farrer, Franck, Georgieff et al., 2003](#)), or using 0–100 point scales of sense of control was employed to evaluate the subjective experience of the movement ([Nahab et al., 2011](#)).

Temporal visual disturbances

Another type of visual disturbance is the use of temporal delays, for instance, [Leube, Knoblich, Erb, and Kircher \(2003\)](#); see also [Leube, Knoblich, Erb, Grodd et al., 2003](#)) used hand opening and closing. Visual feedback of that movement with pseudo-randomized delays between 40ms and 200ms was used. Participants had to evaluate whether or not they experienced a delay. [MacDonald and Paus \(2003\)](#) also used delayed visual feedback of hand movement using a virtual avatar hand that was controlled by a glove. Participants performed voluntary or passive hand movements and were asked whether the image of the

delayed moving hand that they viewed was their own or someone else's, i.e. a self-other discrimination task. In addition, TMS was applied over the parietal or temporal cortex to interfere with the discrimination task. [Shimada, Hiraki, and Oda \(2005\)](#) used delays of passive movement displayed visually to the participants. The participants had to judge whether the feedback was delayed.

Combined temporal and spatial visual disturbances

A combination of temporal and spatial visual disturbances was employed by [Farrer, Bouchereau, Jeannerod, and Franck \(2008\)](#). In this study, participants were asked to perform joystick movements and view the movements on a screen. The entire time they viewed their own hand but were asked to evaluate whether it was (1) their own movement, (2) a modified version of their own movement, or (3) someone else's movement. The experiment used varying spatial disturbances with respect to spatial angle from 0–110° and delays from 0 to 1,300ms. Interestingly, the spatial and temporal disturbances gave rise to very different response patterns. With small deviations (angular and temporal), the participants judged that they themselves were shown on the screen. For intermediate *spatial* deviations, they reported that the feedback was modified, and for large spatial disturbances, they reported that someone else's movement was shown. For *temporal* disturbances, the participant did not ascribe the movement with long delays to someone else, but simply as modified. So, in conclusion, spatial and temporal deviations have very different effects when you have to evaluate between self, biased, or other. The study is framed in terms of the comparator model, and the authors speculate that the two different types of deviations influence goal representation of the action differently. The study highlights two very important aspects of SoA studies. First, the type of deviation matters as to how participants evaluate the movements they are presented with, and second, the types of choices the participants can choose between impact the interpretation of the study.

Action-effect studies

Another type of experiment used to study SoA is what could be described as action-effect studies. The general design of these experiments is such that participants perform an action, and this action leads to a consequence or an effect. An example could be the experiment performed by [Elsner and Aschersleben \(2003\)](#) where a ring attached to a box can be pulled or pushed, and the box can either produce a tone or switch on a light. In this experiment, the effect depends on the action, and a typical manipulation could be to reverse the consequence (tone or light) of the action (push or pull).

By manipulating the outcome of an action, [Sato and Yasuda \(2005\)](#) induced SoA using a simple button press experiment, where participants at their own pace freely pressed two buttons using their left or right index finger. The button press was followed by one of two tones either immediately or after a delay. In a congruent task, the tone following button presses was always the same; in the incongruent task, the tones did not necessarily follow the same button press. Participants had to evaluate on a scale from 0 to 100 whether they agreed with "I was the one who produced the tone" and "I was the one who was listening to the tone". The introduction of the incongruent task diminished SoA.

[Farrer, Valentin, and Hupé \(2013\)](#) used a button press experiment where a delay between the button press and a subsequent movement of a ball was introduced. Participants could evaluate the action effect by judging that either they had full control over triggering the ball, they had partial control over triggering the ball, or that a computer controlled triggering the ball. In this study ([Farrer et al., 2013](#)), the long delay condition gave rise to "other" responses. This is in contrast to the study from 2008, where the long delay conditions did not give rise to "other" responses. So, the response profile for the "delayed effects" in the study from 2013 resemble the response profile of those that are "visually distorted" from the 2008 study. Interestingly, this discrepancy for delayed responses is not discussed, only that a gradual SoA measurement seems more relevant than a dichotic measure of SoA.

Intentional binding

One of the most influential series of studies on implicit measures of SoA is on intentional binding ([Haggard, Clark, & Kalogeras, 2002](#)). The intentional binding experiment derives from the famous Libet clock experiment ([Libet et al., 1983](#)), where participants are watching a rotating clock. At their own will,

participants perform an action and indicate what the time of the rotating clock was when they performed the action or when they intended (felt the urge) to perform the action. In the variant studied by [Haggard et al. \(2002\)](#), participants again had to perform an action (a button press), and the button press caused an auditory tone to follow 250ms later. Now participants had to perform a temporal judgement (using the rotating Libet clock) of when they performed the action or when they heard the tone. These judgements were compared with control situations where participants either had to perform an action without a tone or listen to tones alone, and then judge when the action took place or when the tone was played. In comparison to the control situations, actions that preceded tones were on average judged to be formed later and the tones that followed the actions were judged to be played earlier. This apparent experience of temporal attraction of the action and the effect has been called the intentional binding effect because it only appears when the action is voluntarily produced. When the action was produced by a transcranial magnetic stimulation ([Haggard et al. 2002](#)) over the motor cortex, the temporal attraction of the action and effect was not observed.

The temporal binding phenomenon was suggested as an implicit measure of SoA ([Haggard et al. 2002](#)) and has been used in many subsequent studies as an objective measure of SoA. One of the interesting derived results of the intentional binding experiment has been the introduction of various statistical relationships between actions and their effects. For instance, movements were perceived later when it was more likely that they were followed by an event, and if it was less likely that the movement was followed by an event, it was perceived earlier ([Engbert & Wohlschläger, 2007](#); [Wolpe, Haggard, Siebner, & Rowe, 2013](#)). On this basis, it has been concluded that the contingencies determine the experience of actions ([Moore, Lagnado, Deal, & Haggard, 2009](#)). For a comprehensive review of the intentional binding literature, the reader should consult the study by [Moore and Obhi \(2012\)](#). In addition, [Wolpe and Rowe \(2014\)](#) discuss various ways to address objective measures of agency based on the intentional binding procedures.

Sensory attenuation

One of the underlying reasons for suggesting the idea of internal models in the central nervous system was the principle of sensory attenuation, which is the ability to diminish the sensory effect when one is the cause of the sensory effect, and, in particular, the ability to discriminate between externally generated sensory events and the sensory events one as an organism has produced. To explain this discriminative ability, [von Holst and Mittelsteadt \(1950\)](#) posited the existence of efference copy signals. The effect of sensory attenuation has also been identified in humans when the electroencephalography (EEG) responses to voluntarily generated tones were compared with externally generated tones ([Schäfer & Marcus, 1973](#)), showing a reduced EEG amplitude of auditory evoked potentials when the tones were generated by oneself. This has very recently been studied in relation to SoA, where [Timm, Schönwiesner, Schröger, and SanMiguel \(2016\)](#) found that the N1 component of an auditory evoked response potential was not related to SoA but the P2 component was. The sensory attenuation phenomenon has also been shown in other contexts in humans such as tickling sensations ([Blakemore, Wolpert, & Frith, 2000](#)) and force escalation ([Shergill, Bays, Frith, & Wolpert, 2003](#)).

It is worth noticing that the existence of efference copies was suggested because animals were no longer able to suppress the effect on sensory organs caused by their own movements when the sensory organs were manipulated through surgery. They ended up being unable to adjust their movements appropriately to the environment based on the actual sensory feedback, not because they lacked the sensory feedback, but because their predictions about the sensory consequences of their movements were wrong following the surgery of the sensory organs. This explanatory purpose of the internal models suggests that one cannot really use sensory attenuation paradigms in order to determine whether other types of mechanisms than the comparator may be involved in SoA. A further problem with the use of sensory attenuation as an experimental paradigm in studying SoA is the fact that sensory attenuation is supposed to be the effect of a mechanism for cancelling out signals or at least for dampening them down. This makes it difficult to understand how the paradigm could be used to study the mechanism that is supposed to give rise to a positive SoA signal. If the SoA mechanism is supposed to function in such a way that the better the match between prediction and actual sensory feedback, the stronger the signal for agency (the stronger the SoA), then this SoA mechanism does not have the properties of a sensory attenuation mechanism, according to which the better the match, the more the signal is dampened down.

Discussion of experimental approaches to SoA studies

It is clear that most of the previously mentioned studies employ an experimental approach where a movement, usually a button press, elicits some kind of external event such as a tone or something that moves on a screen. In some cases, this event resembles a delayed version of the actual movement performed using a delayed video signal. However, none of the presented studies addresses the narrow SoA of actual movement without external consequence. What is evident from our review is the lack of SoA studies of the movement itself. All existing studies (as far as we know) examine movements *and* their external consequences – except of course for some sensory attenuation studies, which for the reasons discussed previously should be rejected as an appropriate way to study the sense of movement activity.

So why is there a lack of SoA experiments that directly address the sensations related to agency of the actual movement itself? Our proposal is that one important reason is the definitions of SoA available in the contemporary literature – in particular, the broad definition of SoA and the definition of SoA in terms of self-other discrimination. Many researchers have adopted a broad definition of SoA as the sensation of being the author of an action *and its consequences*. If one has defined SoA in relation to action consequences, one might not be motivated to dissociate the “agency” of a movement from agency of an action and its consequences.

As our discussion of definitions of SoA demonstrated, many researchers understand SoA as an inquiry into whether an action is produced by oneself or another agent. If we accept that agents are separated by their outer boundaries (Friston, 2013), it would seem there would be no reason for thinking that movement “within these boundaries” could ever be mistaken with movements of another agent. If we think SoA plays an important role in self-other discrimination, then external sensory events would seem the appropriate domain.

Broad definitions of SoA are probably part of the explanation for the near total dominance of action-consequence paradigms. A narrow definition of SoA in terms of the sense of movement activity does not fit so easily with the experimental focus on action effects. Let us end this section by flagging a possible complementary and much more practical explanation. A final suggestion as to why there are no SoA experiments that address the actual movements may be that it is simply very difficult to manipulate the proprioceptive feedback while performing a movement.

Concluding remarks

Summing up the argument thus far, there are reasons for assuming that agents of bodily actions experience a sense of activity in relation to their physical movement. A brief review of the various definitions of SoA demonstrated that this sense of movement activity often is acknowledged as part of a more global SoA. The global or broad conception of SoA includes the action in preparatory, movement, and environmental consequence stages.

We subsequently reviewed some of the dominant theoretical models of SoA. These models differ along a number of different dimensions. One dimension is how well equipped a model is to explain motor control and the sense of activity associated with the execution of particular movements. Some version of the comparator model is perhaps the model best placed to account for motor control. We argued that the comparator model is faced with two problems. First, the comparator model is too often called upon to explain the SoA for events (e.g. environmental sensory consequences) that a comparator model *strictu sensu* could not explain on its own. Second, the original motivation for postulating a comparator mechanism in motor control was to explain sensory attenuation. If the comparator mechanism is a mechanism dampening down the sensation of self-produced proprioceptive and tactile signals, then it does not seem to be a good candidate for explaining the sense of movement activity. We made the simple suggestion that the sense of movement activity is associated directly with motor command signals. It is an open question if any of the dominant theoretical models is consistent with this suggestion.

Finally, we reviewed standard paradigms used to study the SoA. The upshot of this review is that even if we had the theoretical models to explain the sense of movement activity, we do not have the paradigms. The review shows us that either the paradigms target the SoA for action consequences or, if they actually do directly study bodily sensations, they concern sensory attenuation. At present, we do not have paradigms to isolate the sense of movement activity from the SoA for environmental events. We do not have paradigms that

could help us distinguish between the various theoretical models of the sense of movement activity. A major task for future studies of SoA is therefore to develop new experimental paradigms.ⁱ

Note

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